

A new analysis of quasar polarisation alignments

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Abstract

We propose a new method to analyse the alignment of optical polarisation vectors from quasars. This method leads to a definition of intrinsic preferred axes and to a determination of the probability p^σ that the distribution of polarisation directions is random. This probability is found to be as low as $3.0 \cdot 10^{-5}$ for one of the regions of redshift.

1 Introduction

Fifteen years ago, Hutsemékers discovered that the optical polarisation vectors from distant quasars are not randomly distributed [Hutsemékers 1998]. The original study considered a sample of 170 quasars, and the probability of a random distribution was 0.5 %. Since then, further measurements have been added [Hutsemékers & Lamy, 2001, Sluse et al. 2005, Hutsemékers et al. 2005], and the significance of the effect has grown: with the present sample of 355 polarisation data points, the alignment effect has been estimated to have a probability to be random lower than 0.1 % in some regions of the sky defined by cuts on right ascension and redshift.

The original test however had a weak point, as the angles of the polarisation vectors are measured with respect to their local meridian. Therefore, the strength of the alignment, and the significance of the effect, depend on the choice of the spherical coordinate system, so that it is possible to find an axis for which the effect becomes negligible, i.e. for which the data look random. Indeed, the original statistical tests do not take into account the fact that polarisation vectors come from different lines of sight and thus are not defined in the same plane. To remedy this problem, [Jain, Narain & Sarala, 2004] have proposed to parallel-transport the polarisation vectors along geodesics of the celestial sphere onto one point in order to compare them. While the distribution of polarisation angles still depends on the point where it is built, it does not depend on the coordinates, and one can build robust statistical tests (see Jain et al. (2004) and Hutsemékers et al. (2005)). Unfortunately, these tests have to resort to the generation of a large number of random data in

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order to determine the significance of the signal and do not lead to a clear characterization of the effect. Furthermore, to make an intrinsic test, polarisation vectors must be transported to the location of the quasars. However, this is an arbitrary choice as they can be transported to any point on the celestial sphere. The sum of the parallel-transported polarisation vectors then makes a continuous axial vector field on the sphere, and by the hairy ball theorem [Eisenberg & Guy, 1979], it is still possible to find at least two points where the effect vanishes. Hence the quantification of the size of the effect seems uncertain again.

We propose here another method which is totally independent of the coordinate system, and which quantifies unambiguously the alignment effect. It allows us to compare the polarisation vectors of sources located at different angular coordinates and leads to the characterization of the effect through a blind analysis of the data. The basic idea is to consider the physical polarisation vectors as 3-dimensional objects rather than 2-dimensional ones embedded in their polarisation plane. These 3-dimensional objects are the directions of the electric field oscillations and they are the physical objects which are measured. As we are dealing with a number of vectors, it is clear that it will be possible to define preferred directions. We can also use the same method to study the dependence on redshift, position in the sky or degree of linear polarisation by imposing cuts on these variables and repeating the study for the corresponding sub-sample.

We devote the present paper to the construction of this new statistical method applied here to the analysis of quasar polarisation data, in which the evaluation of the significance of the signal will be largely analytic. The second section of this paper explains the details of our statistical method. It also contains illustrations and discussions related to the statistical background, when polarisation angles are assumed to be uniformly distributed, and is compared with the original study of [Hutsemékers et al. 2005] using the same cuts. The third section is devoted to the application of this new statistical method first globally, then to slices in redshift. We also consider there the dependence of the alignment on the various parameters, the possibility of a cosmological alignment, and define our final most significant regions exhibiting an anomalous alignment of polarisation vectors.

2 A coordinate-invariant statistical test for polarisation data

When an electromagnetic wave is partially or fully linearly polarized, a polarisation vector is introduced. Its norm reflects the degree of linear polarisation of the radiation while its direction is that of the oscillating electric field. This vector is thus embedded into the plane orthogonal to the radiation direction of propagation, the polarisation plane. Since the electric field is oscillating, the polarisation vector is an axial quantity, rather than a true vector, so that the polarisation angle is determined up to π radians.

We consider sources as being points on the unit celestial sphere and we choose a spherical polar coordinate system defined by the orthonormal 3-vectors $(\mathbf{e}_r, \mathbf{e}_\theta, \mathbf{e}_\phi)$, with \mathbf{e}_θ pointing to the South pole. In the following bold-faced letters indicate 3-vectors. Polarisation vectors are tangent to this unit sphere. For a given source in the direction \mathbf{e}_r , a polarisation vector must lie in the plane defined by the two unit vectors \mathbf{e}_ϕ and \mathbf{e}_θ . We choose the angle ψ

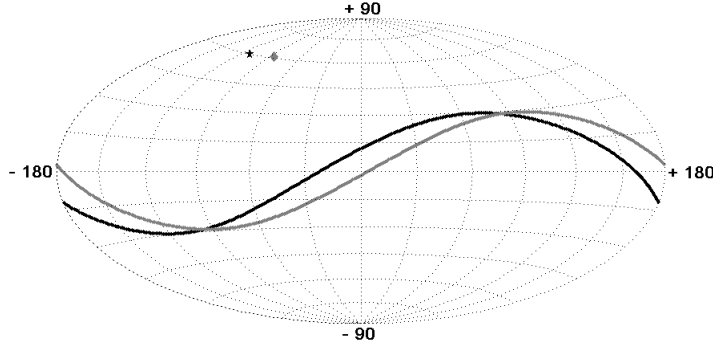


Figure 1: Superposition of the Hammer-Aitoff projections of the celestial sphere and the polarisation sphere (in galactic coordinates). Two quasars (B1115+080 (in black) and B1157+014 (in grey)) are displayed on the celestial sphere with the corresponding geometric loci of their polarisation point on the polarisation sphere. The source position and the corresponding geometric locus of the polarisation point are printed in same brightness.

between the polarisation vector \mathbf{p} and the basis vector \mathbf{e}_ϕ , defined in the range $[-\pi/2, \pi/2[$, to be the polarisation angle. The normalized polarisation vector can then be written

$$\hat{\mathbf{p}} = \cos\psi \mathbf{e}_\phi - \sin\psi \mathbf{e}_\theta . \quad (1)$$

Each measurement (i) of the dataset [Hutsemékers et al. 2005] is equivalent to a position 3-vector $\mathbf{e}_r^{(i)}$ associated with a normalised polarisation direction $\hat{\mathbf{p}}^{(i)}$ and polarisation magnitude $|\mathbf{p}^{(i)}|$. Contrarily to the various angles, $\mathbf{e}_r^{(i)}$ and $\hat{\mathbf{p}}^{(i)}$ are physical, *i.e.* they do not depend on the choice of coordinates. As we are interested in polarisation alignments, we shall consider mostly the $\hat{\mathbf{p}}^{(i)}$ in the following.

The problem is then as follows: we have a number of normalised vectors, and we want to decide if they are abnormally aligned. We can draw them from the same origin, and their ends, which we shall call the polarisation points, have to lie on a unit 2-sphere, which we shall refer to as the polarisation sphere. The problem is that, even when the polarisation angles ψ are uniformly distributed, the polarisation sphere is not uniformly covered by the points: they have to lie on great circles on the 2-sphere. Indeed, for each source, the polarisation vectors are constrained to be in the plane defined by the basis vectors $(\mathbf{e}_\phi^{(i)}, \mathbf{e}_\theta^{(i)})$. The intersection of the plane with the polarisation sphere is a great circle, which is the geometric locus where the polarisation vector attached to the source (i) may intersect the sphere, as shown in Fig. 1. Note that the figure is symmetric as polarisation vectors are defined up to a sign. In the following, we choose to show the full sphere, although a half-sphere could be used to represent the polarisation space.

To compare the observations with what one would expect if the polarisation points were drawn from a random distribution of polarisation angles, we need to select a region on the polarisation sphere, count the number of polarisation points within this region, and compare

this number with the prediction. One could do this by Monte-Carlo techniques, but as we shall see the probabilities turn out to be rather low, so that a detailed study would prove difficult.

However, we found that a particular choice of shape for the region on the sphere considerably simplifies the evaluation of probabilities. We consider cones in which the polarisation vectors fall, or equivalently spherical caps of fixed aperture angle. The probability distribution of a given number of points in a given spherical cap can be computed analytically as explained below. A scan of the whole polarisation half-sphere leads to a map of expected densities which constitutes the statistical background. At any location on the half-sphere, the hypothesis of uniformity can then be tested by calculating the probability of the observed number of polarisation points. An alignment of polarisation vectors from different sources will be detected when an over-density between data points and the background is significant.

2.1 Construction of the probability distribution

As mentioned above, the locus of the polarisation points is a half-circle in the plane normal to the source position vector. The probability that a polarisation point lies inside a spherical cap is then given by the length of the arc of circle intercepted by the cap, divided by the whole length of the half-circle (π). Let η being the half-aperture angle of the spherical cap, and $\hat{\mathbf{s}}$ the unit vector pointing to its centre. If $\hat{\mathbf{p}}^{(i)}$ is a normalised polarisation vector attached to the source (i), with position vector $\mathbf{e}_r^{(i)}$, the corresponding polarisation point lies inside the spherical cap centred at $\hat{\mathbf{s}}$ if and only if

$$|\hat{\mathbf{p}}^{(i)} \cdot \hat{\mathbf{s}}| \geq \cos \eta \quad (2)$$

is verified. Adopting the decomposition of $\hat{\mathbf{p}}^{(i)}$ along two vectors in the polarisation plane

$$\hat{\mathbf{p}}^{(i)} = A (\hat{\mathbf{s}} - (\hat{\mathbf{s}} \cdot \mathbf{e}_r^{(i)}) \mathbf{e}_r^{(i)}) + B \hat{\mathbf{t}}^{(i)} \quad (3)$$

where $\hat{\mathbf{t}}^{(i)} = (\mathbf{e}_r^{(i)} \times \hat{\mathbf{s}}) / |\mathbf{e}_r^{(i)} \times \hat{\mathbf{s}}|$, a straightforward calculation involving the normalisation of $\hat{\mathbf{p}}^{(i)}$ and the condition for being inside the spherical cap leads to the arc length $L^{(i)}$ of the geometric locus lying inside the considered area. The result takes a simple form in terms of $\tau^{(i)} \in [0, \pi[$, the angle between $\mathbf{e}_r^{(i)}$ and $\hat{\mathbf{s}}$: condition (2) becomes $\sin \tau^{(i)} \geq \cos \eta$ and, by integration of the line element, the arc length within the cap is found to be:

$$L^{(i)} = \begin{cases} 2 \arccos \left(\frac{\cos \eta}{\sin \tau^{(i)}} \right) & \text{if } \sin \tau^{(i)} \geq \cos \eta \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

Therefore, the probability $\ell^{(i)}$ that the i -th source of the sample leads to a polarisation point inside a given spherical cap is:

$$\ell^{(i)} = \frac{L^{(i)}}{\pi}. \quad (5)$$

Hence, these probabilities only depend on the chosen aperture angle of the spherical cap and on the angle between the source positions and the cap centre. These probabilities are thus completely independent of the system of coordinates.

For each cap, the set of probabilities $\ell^{(i)}$ leads to the construction of the probability distribution P_n of observing exactly n points of polarisation inside the spherical cap. If N is the sample size we have:

$$P_0 = \prod_{i=1}^N (1 - \ell^{(i)}) \quad (6)$$

$$P_1 = \sum_{j=1}^N \ell^{(j)} \prod_{i \neq j} (1 - \ell^{(i)}) \quad (7)$$

$$P_2 = \frac{1}{2} \sum_{k=1}^N \ell^{(k)} \sum_{j \neq k} \ell^{(j)} \prod_{i \neq j \neq k} (1 - \ell^{(i)}) \quad (8)$$

\vdots

$$\begin{aligned} P_N &= \frac{1}{N!} \sum_{l=1}^N \ell^{(l)} \dots \sum_{j \neq \text{prev. indices}} \ell^{(j)} \prod_{i \in \{\emptyset\}} (1 - \ell^{(i)}) \\ &= \prod_{l=1}^N \ell^{(l)} \quad . \end{aligned} \quad (9)$$

Note that following the previous definitions, it is possible to write, for each n ,

$$P_n = \frac{1}{n} \sum_{j=1}^N \ell^{(j)} P_{n-1 \setminus j} \quad (10)$$

where $P_{n-1 \setminus j}$ is the probability to observe $n-1$ points of polarisation (and only $n-1$) after the j -th element is removed from the original sample, making the new sample size $N-1$.

2.2 A fast algorithm for generating the P_n

Starting with the entire sample of size N , let us consider the probability P_0 to observe no polarisation point within the cap. We remove the k -th element from this sample. Then, from equation (6), the probability to observe no polarisation point within this reduced sample, denoted by $P_{0 \setminus k}$, is related to P_0 through $P_0 = \ell^{(k)} P_{0 \setminus k}$, where we introduced the following notation for the probability that the source k does not lead to a polarisation point in the concerned area : $\ell^{(k)} \equiv (1 - \ell^{(k)})$.

First consider the probability P_1 to observe one and only one polarisation point:

$$\begin{aligned}
P_1 &= \sum_{j=1}^N \ell^{(j)} \prod_{i \neq j} \ell^{(i)} \\
&= \sum_{j=1}^N \ell^{(j)} P_{0 \setminus j} \\
&= \sum_{j \neq k} \frac{\ell^{(j)}}{\ell^{(j)}} P_0 + \ell^{(k)} P_{0 \setminus k} \\
&= \ell^{(k)} \left(\sum_{j \neq k} \frac{\ell^{(j)}}{\ell^{(j)}} P_{0 \setminus k} \right) + \ell^{(k)} P_{0 \setminus k} \\
&= \ell^{(k)} P_{1 \setminus k} + \ell^{(k)} P_{0 \setminus k} \quad .
\end{aligned} \tag{11}$$

A similar calculation leads to $P_2 = \ell^{(k)} P_{2 \setminus k} + \ell^{(k)} P_{1 \setminus k}$. One can prove by induction that the following relation holds:

$$P_m = \ell^{(k)} P_{m \setminus k} + \ell^{(k)} P_{m-1 \setminus k} \tag{12}$$

Indeed, assuming the relation is true for $m \leq n-1$, it is easy to show that it is then true for $m = n$:

$$\begin{aligned}
P_n &= \frac{1}{n} \sum_{l=1}^N \ell^{(l)} P_{n-1 \setminus l} \\
&= \frac{1}{n} \sum_{l \neq k} \ell^{(l)} P_{n-1 \setminus l} + \frac{1}{n} \ell^{(k)} P_{n-1 \setminus k} \\
&= \ell^{(k)} \left(\frac{1}{n} \sum_{l \neq k} \ell^{(l)} P_{n-1 \setminus l \setminus k} \right) \\
&\quad + \ell^{(k)} \left(\frac{1}{n} \sum_{l \neq k} \ell^{(l)} P_{n-2 \setminus l \setminus k} \right) + \frac{1}{n} \ell^{(k)} P_{n-1 \setminus k} \\
&= \ell^{(k)} P_{n \setminus k} \\
&\quad + \ell^{(k)} \left(\frac{n-1}{n} \left[\frac{1}{n-1} \sum_{l \neq k} \ell^{(l)} P_{n-2 \setminus l \setminus k} \right] \right) \\
&\quad + \ell^{(k)} \frac{1}{n} P_{n-1 \setminus k} \\
&= \ell^{(k)} P_{n \setminus k} + \ell^{(k)} P_{n-1 \setminus k} \quad .
\end{aligned} \tag{13}$$

Therefore, equation (12) holds¹ for every $m \in \mathbb{N}$. Assuming that, for a sample of size N and for a given spherical cap, we have all elementary probabilities $\ell^{(i)}$, we use the following algorithm for numerically computing the probability distribution:

¹Equation (12) was first introduced by Howard (1972) and its numerical behaviour was extensively discussed in the paper [Chen & Liu, 1997] about computational techniques for the Poisson-binomial probabilities. The algorithm presented here is equivalent to that given in [Chen & Liu, 1997].

- 1) We introduce a column vector V of size $N + 1$, initialized to zero, except for V_0 which is set to 1. The V_n are the P_n for an empty data set.
- 2) We add one data point at a time, and update V according to equation (12).
- 3) After N iterations, the V_n give the P_n distribution for the studied sample².

2.3 A first example

To illustrate the use of the above, we show in Fig. 2 a map of the expected background for region A1 of [Hutsemékers et al. 2005], as defined in Table 1.

region	declination	right ascension	redshift	number of quasars
A1	$\delta \leq 50^\circ$	$168^\circ \leq \alpha \leq 217^\circ$,	$1.0 \leq z \leq 2.3$	56
A2	$\delta \leq 50^\circ$	$150^\circ \leq \alpha \leq 250^\circ$	$0.0 \leq z < 0.5$	53
A3		$320^\circ \leq \alpha \leq 360^\circ$	$0.7 \leq z \leq 1.5$	29

Table 1: The three regions of alignment of in equatorial coordinates B1950.

At each point a of the polarisation sphere we associate a probability distribution P_n^a through the use of spherical caps. The mean values $\bar{N}^a = \sum_n n P_n^a$ determine the most expected number of polarisation points. From those numbers, we build iso-density regions on the polarisation sphere in order to visualize the structure that the statistical background takes. We arbitrarily choose here caps of half aperture $\eta = 17^\circ$. The dependence of the results on η will be discussed in section 2.4.3.

Due to the non uniformity of the source locations, there are regions of maxima (and minima) in the expected densities of polarisation points as well as regions where polarisation points are forbidden. For this sample, a close look at Fig. 2 shows that a quadrupole is naturally expected in the density structure on the polarisation sphere. This shows that the use of the P_n distributions is mandatory, as the expected density is not flat.

2.4 Further refinements of the method

2.4.1 Optimal set of centres for the spherical caps

The method presented so far has two problems:

- Several spherical caps can contain the same polarisation points, so that several probability distributions are assigned to the same set of data points.

²We have tested our implementation of the algorithm by comparing its results to those obtained via a Monte-Carlo treatment, for the A1 region of reference [Hutsemékers et al. 2005]. We produced 10000 random samples, for which the quasar positions were kept fixed and for which the polarisation angles were randomly generated according to a uniform distribution. For different spherical caps we built the corresponding P_n distributions, and found a perfect agreement. We checked that the same conclusions are obtained for the whole sample of quasars presented in [Hutsemékers et al. 2005] and for arbitrary sub-samples.

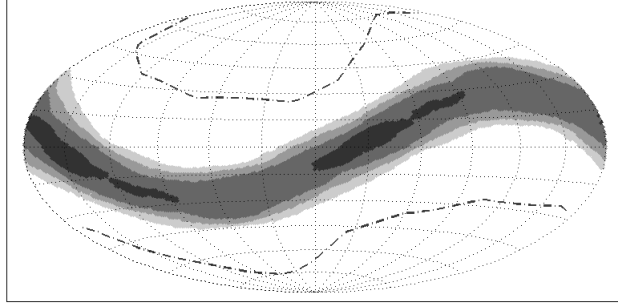


Figure 2: Hammer-Aitoff projection (galactic coordinates) of the polarisation sphere associated to the A1 region. Expected density regions are displayed following the legend: white: $\bar{N}^a < 4$; light grey: $4 \leq \bar{N}^a < 5$; grey: $5 \leq \bar{N}^a < 6$; dark grey: $6 \leq \bar{N}^a < 7$; black: $\bar{N}^a \geq 7$. White regions towards poles which are delimited by dashed curves are regions where polarisation points cannot fall at all.

- Among the caps containing the same data points, the most significant ones will be those for which several of the $\ell^{(i)}$ will be small, i.e. for which the loci of several polarisation points are almost tangent to the caps. This enhanced significance is an artefact of our method.

In order to minimize these problems, we do not allow all caps to be considered, but rather focus on those that correspond to cones with an axis along the vectorial sum of the normalised polarisation vectors inside them. Hence the effective polarisation vector corresponding to the centre of the cap is

$$\mathbf{s}_{centre} = \sum_{i \in cap} \hat{\mathbf{p}}^{(i)}, \quad \hat{\mathbf{s}}_{centre} = \frac{\mathbf{s}_{centre}}{|\mathbf{s}_{centre}|}$$

These centres are first determined by iteration before applying the algorithm explained above.

2.4.2 Local p-value of the data

The study of alignments is performed separately for each cap a on the polarisation sphere, for which we derive probability distributions P_n^a . In each cap, we count the number o_a of observed polarisation points, and $P_{o_a}^a$ gives us the probability that the presence of o_a polarisation points in cap a is due to a background fluctuation. The probability that a generation from a uniform background has a density greater than the observed one is given by the p-value $p^a = \sum_{n \geq o_a} P_n^a$. The latter quantity gives us the significance level of a specific polarisation point concentration in one given direction. As already mentioned, equation (5) shows that p is coordinate invariant. It in fact provides a generalisation of the binomial test used in [Hutsemékers 1998, Hutsemékers & Lamy, 2001, Hutsemékers et al. 2005]. For each sample, we can consider the cap a_{min} that gives the most significant p-value $p_{min} = \min_a(p^a)$

which we shall call the significance level. This defines a direction in polarisation space, and a plane in position space.

2.4.3 Dependence on the spherical cap aperture

The only free quantity in this method is the aperture half-angle of the spherical caps.

For a given sample of sources we perform the study for a wide range of half-aperture angle. For each of them we determine the optimum cap centres, and calculate p_{min} as a function of η . Fig. 3 shows p_{min} as a function of η for sub-samples A1, A2 and A3, as defined in [Hutsemékers et al. 2005], for η taking all integer values between 15 and 50 degree.

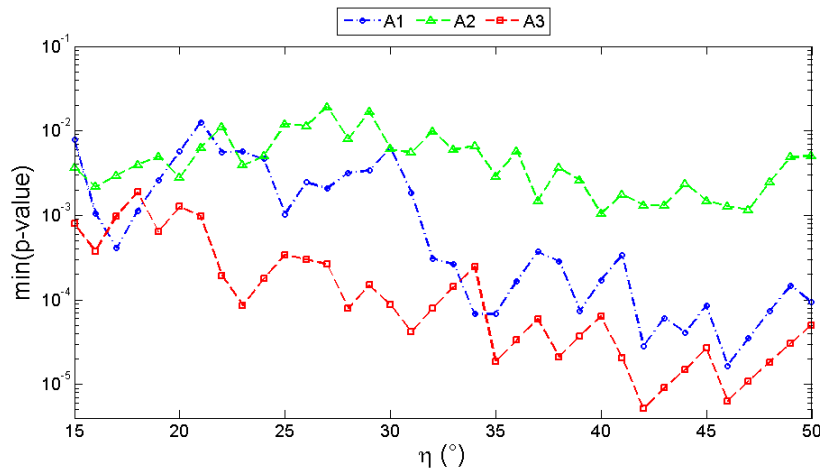


Figure 3: Dependence of the significance level with η , the half-aperture angle of spherical caps (in degree). The regions are defined as in Table 1.

Fig. 3 shows that the different samples present significant over-densities of polarisation points. We see that p_{min} is smaller for η between 30° and 50° , depending on the sample. The role of η is somewhat similar to that of the number of nearest neighbours used in [Hutsemékers 1998], [Hutsemékers et al. 2005] and [Jain, Narain & Sarala, 2004], and it has a physical meaning. First of all, each polarisation cap corresponds to a band in the sky, which has an angular width of 2η . Hence, η selects part of the celestial sphere. Secondly, as the sources are angularly separated and as quasar polarisation vectors are always perpendicular to the line of sight, their projections to the centre of the polarisation sphere will always be spread. η takes this spread into account. Finally, η is linked to the strength of the effect (more on this in section 3.4). A very strong alignment will gather the polarisation points in a small cap, due only to the spread of the sources. A weaker one will necessitate larger caps, as the effect will be added to a random one that produces a large spread on the polarisation sphere. We thus see that η is determined by physical parameters: the spread of the sources and the strength of the effect. It thus seems reasonable to determine its optimal value, which we shall do in the next subsections.

2.4.4 Global significance level of the effect

So far, we have considered the probability that an over-density in a given cap be due to a background fluctuation. A more relevant probability maybe that of the occurrence of such an over-density anywhere on the polarisation sphere. To calculate this, we have resorted to a Monte-Carlo treatment, generating for each data sample N_s simulated datasets, in which we consider only the quasars of that dataset, keep their positions fixed on the sky, and randomly vary their polarisation angles according to a flat distribution. For a given data sample, we introduce a global significance level p^σ defined as the proportion of random sets which produce p-values smaller or equal to p_{min} somewhere on the polarisation sphere.

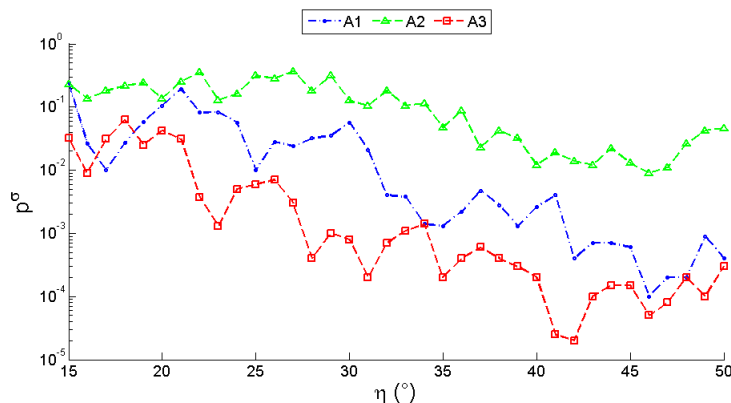


Figure 4: Behaviour of the global significance level with the half-aperture angle for the A1, A2 and A3 regions of Table 1.

2.4.5 Optimal angle for the spherical caps

Fig. 4 shows the behaviour of the global significance level p^σ with the aperture angle of the spherical caps for the sub-samples A1, A2 and A3. Comparing Figs. 3 and 4, we note that p^σ and p_{min} follow the same trend. Clearly, the relation between them must involve the number of possible caps N_c , and p^σ would be equal to $N_c p_{min}$ if the caps did not overlap and if all simulated datasets had the same number of caps. Hence we expect N_c to be of the order of the area of the half-sphere divided by the area of a cap, $p^\sigma \approx p_{min} / (1 - \cos\eta)$. We found empirically that this relation underestimates p^σ by a factor smaller than 4, for all the samples we analysed.

Table 2 shows the significance levels p_{min} of over-densities obtained for the different samples of quasars, compared with the binomial probability P_{bin} reported in [Hutsemékers et al. 2005]. Note that a spherical cap is in general sensitive only to sources along a band of the celestial sphere so that only part of the entire data sample can contribute to it. We thus compare the number of polarisation points in the cap o_a to the maximum number of points possible in that cap, o_a^{max} .

region	P_{bin}	p_{min}	$\eta(^{\circ})$	o_a/o_a^{max}	p^{σ}
A1	$3.3 \cdot 10^{-6}$	$1.7 \cdot 10^{-5}$	46	43/56	$1.0 \cdot 10^{-4}$
A2	—	$1.7 \cdot 10^{-3}$	46	32/47	$0.9 \cdot 10^{-2}$
A3	$2.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-6}$	42	25/29	$2.7 \cdot 10^{-5}$

Table 2: Significance levels for various data samples. o_a is the number of polarisation points inside the spherical cap where the minimum significance level (minimum p-value) p_{min} is observed, o_a^{max} is the maximum number of polarisation points that might fall inside this cap, η is the half-aperture angle of the cap, P_{bin} is the binomial probability obtained in [Hutsemékers et al. 2005] (Table 1) and p^{σ} is the global significance level of the region obtained through the method explained in section 2.4.4.

We see from Table 2 that the best half-aperture angle depends on the region, and that it is large: 42 or 46 degrees.

We also see that the regions A1 and A3 defined in [Hutsemékers et al. 2005] are the most significant with our algorithm. However, we need to know whether the difference between P_{bin} and p_{min} is important. We shall then study the errors on the significance level and on η and see that the discrepancies are reasonable.

To do so, we perform a Jackknife analysis, removing in turn each quasar from a given sample, and performing the analysis again. The results are show in Fig. 5.

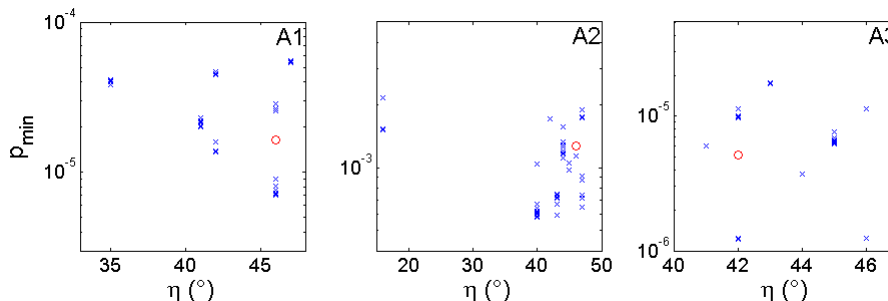


Figure 5: Result of the Jackknife methods for regions A1, A2 and A3. The red circles correspond to the results of Table 2.

We see that the errors on η are large, and that p_{min} can go up or down by a factor of the order of 3. Hence it seems that our method really agrees with the estimates of [Hutsemékers et al. 2005]. One also clearly sees that region A2 is less significant than A1 and A3. In the following, given the large uncertainties, we choose to fix the angle η at 45° . Note that the local and global significance levels we give could be slightly improved if we chose a different value of η for each sample.

3 Results

We now have a coordinate-invariant statistical test which depends only on the half-aperture angle of the caps and which takes into account the dispersion of sources on the sky. As

explained above, we fix the half-aperture to 45° .

We can then scan the polarisation sphere with caps, and assign a value of p_{min} to each. The most significant deviations can be kept and we can numerically evaluate the global significance p^σ for the same sample.

This can be done not only on the full data sample, but also on sub-samples corresponding to regions of redshift, declination or right ascension, or to cuts on the degree of polarisation. We shall consider these various cases in the following subsections.

3.1 Full sample

The full sample of quasars is naturally split into galactic North and galactic South because the observations are away from the galactic plane, so that besides the whole sample, we shall also consider all the northern quasars or all the southern ones. Each sample has respectively 355, 195 and 160 sources.

Sample	p_{min}	$(\delta, \alpha)_{a_{min}} (^\circ)$	o_a/o_a^{max}	$(\delta, \alpha)_{\langle \mathbf{e}_r \rangle} (^\circ)$	p^σ
Whole	$1.5 \cdot 10^{-2}$	(48.6, 283.7)	163/318	(5.5, 185.0)	0.14
Northern sky	$9.3 \cdot 10^{-2}$	(23.1, 294.0)	82/173	(12.2, 197.2)	0.58
Southern sky	$5.1 \cdot 10^{-5}$	(39.7, 270.6)	89/142	(-0.7, 358.5)	$6.0 \cdot 10^{-4}$

Table 3: Parameters of the most significant caps.

We consider all the possible spherical caps, and show the most significant ones in Table 3. The first column gives the most significant p-value, the equatorial coordinates in the polarisation space $(\delta, \alpha)_{a_{min}}$ of the centre of the most significant cap, and the ratio of the number of quasars within the cap to the maximum number, o_a/o_a^{max} . We also give the angular coordinates of the vector $\langle \mathbf{e}_r \rangle$ resulting from the normalized sum of the position vectors of the o_a sources and the global significance level p^σ of the alignment. From this table, one sees that nothing is detected in the whole sample or in the northern one. On the other hand, an alignment is detected towards the galactic South. One may wonder then how it was possible to find the significant alignments A1 and A2 towards the galactic North, as in Tables 1 and 2. The reason for this is that so far we have considered all data points, *i.e.* all redshifts, all declinations, and all right ascensions. The fact that there is an alignment to the South and not to the North tells us that the effect depends on the physical position of the sources. Hence when we consider all sources, we average the effect, and can simply destroy it.

To illustrate this, we can consider the redshift distribution of the quasars contributing to the alignment seen towards the galactic South. Simply counting the aligned quasars in regions of redshift is not enough, though, as the statistics of the sample varies, and as only some quasars have trajectories in polarisation space that can intercept the considered cap. However, we have already the required tool: for a fixed cap, we can consider slices of redshift and their p-value. Fig. 6 shows the p-values of slices in which there is an excess. We can clearly see in it that the alignment is concentrated in a reduced region of redshift starting at $z = 0.8$.

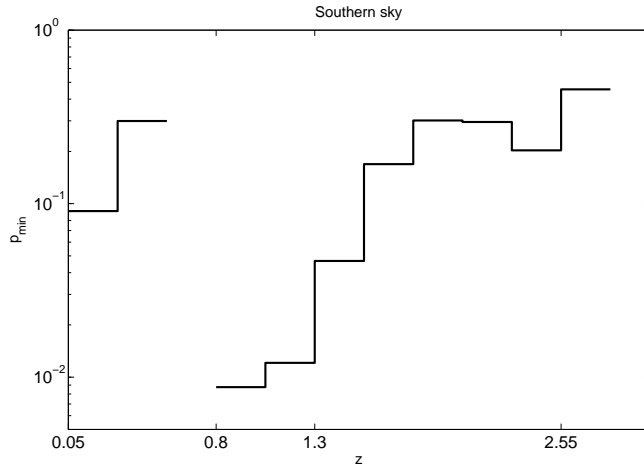


Figure 6: The p-value distribution of the slices of redshift that display an excess of aligned polarisations, for quasars of the southern sample.

It is indeed known [Hutsemékers & Lamy, 2001], [Hutsemékers et al. 2005], [Hutsemékers et al. 2010], [Hutsemékers et al. 2011], [Jain, Narain & Sarala, 2004] that the directions of large-scale alignments of optical polarisation orientations of quasars show a dependence on the redshift of the sources. Hence studying the effect globally may not make sense, and different alignments at different redshifts may cancel each other. Also, if only some regions of redshift have an alignment effect, then it can get washed out globally.

Concentrating on the most significant region of Fig. 6 is not consistent either, as the cap which it is built from is influenced by the unaligned quasars at high and low redshift. In the next section, we shall develop a method to find the regions of redshift where the quasars are strongly aligned.

3.2 Redshift dependence

The problem is thus to make a blind analysis of the redshift dependence of the alignment. To do so, we consider a slice of redshift $[z_{min}, z_{max}]$ and calculate the p-value of the quasars falling in it. We then vary z_{min} and z_{max} on a grid. The size of the steps δz in z_{min} and z_{max} will of course depend on the statistics of the data.

We show the redshift distribution of the data in Fig. 7. We see that the high-redshift data points ($z > 2.5$) are few, and that there is another deficit in the southern sample in the region $[1.5, 1.7]$. Also, we see that a bins of width $\delta z = 0.1$ allow reasonable statistics for most redshifts.

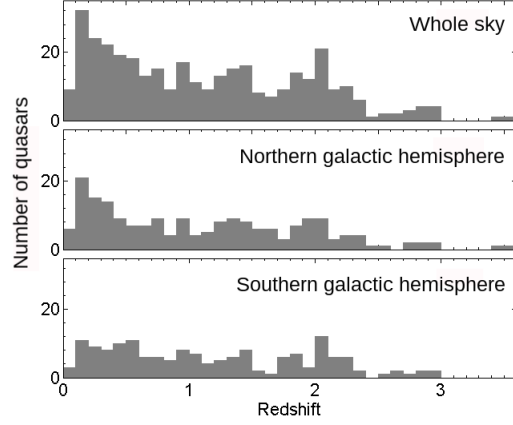


Figure 7: The redshift distribution of the sample of 355 quasars with bin width of $\Delta z = 0.1$ are shown for the whole sky, the northern galactic hemisphere and the southern galactic hemisphere. The last bin in the whole sky and northern histograms contains the quasar at $z = 3.94$.

We can now consider all the values of z_{min} and z_{max} on a grid of spacing 0.1 (we also exclude the one quasar with $z > 3$). As our test does not use the quasar position (although it depends on it), we do not need to introduce further cuts by hand as in [Hutsemékers 1998] and [Hutsemékers et al. 2005]. We nevertheless consider the whole sample, and the northern and southern regions separately. We show in Fig. 8 the result of this study.

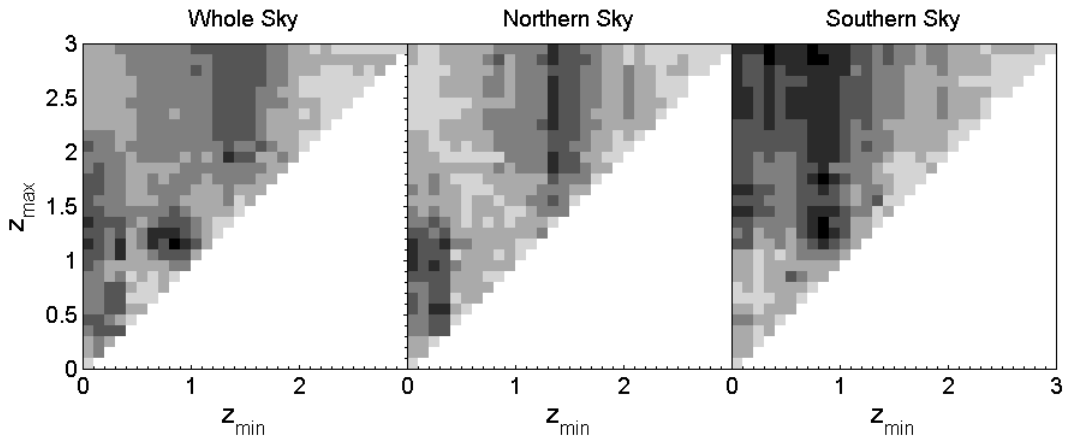


Figure 8: Contour plots of p_{min} as a function of the minimum and maximum values of the redshift, for the whole sample, for the galactic North and for the galactic South. Values from 10^{-6} to 10^{-5} are in black, and the different nuances of grey correspond to factors of 10, up to the white regions, which are for p_{min} between 0.1 and 1.

For a given region $[z_{min}, z_{max}]$ we show the value of p_{min} as different shades of grey, the darkest regions being the most significant. Clearly, the dependence on redshift does

Sample	z_{min}	z_{max}	p_{min}	$(\delta, \alpha)_{a_{min}} (^\circ)$	o_a/o_a^{max}	$(\delta, \alpha)_{\langle e_r \rangle} (^\circ)$	p^σ
W0	0.3	1.1	$2.9 \cdot 10^{-5}$	(20.7, 304.3)	60/99	(16.9, 203.3)	
W1	0.8	1.2	$7.3 \cdot 10^{-6}$	(25.4, 278.1)	31/40	(12.2, 181.2)	
W2	1.3	2.0	$8.3 \cdot 10^{-5}$	(76.0, 304.7)	53/80	(10.2, 32.4)	
WCo	1.3	2.0	$4.3 \cdot 10^{-6}$	(65.9, 293.1)	39/50	(−9.3, 3.5)	$2.7 \cdot 10^{-5}$
N0	0.2	0.6	$1.4 \cdot 10^{-5}$	(15.0, 308.2)	28/37	(22.3, 208.4)	$1.8 \cdot 10^{-4}$
N1	0.3	1.2	$1.5 \cdot 10^{-5}$	(12.7, 305.0)	40/58	(19.3, 206.4)	
N2	1.3	2.0	$3.5 \cdot 10^{-5}$	(78.2, 298.1)	35/47	(5.8, 186.6)	$3.4 \cdot 10^{-4}$
S0	0.3	2.9	$8.1 \cdot 10^{-6}$	(44.7, 273.8)	79/120	(−5.0, 357.1)	
S1	0.7	3.0	$3.1 \cdot 10^{-6}$	(43.6, 272.3)	62/89	(−7.0, 357.6)	
S2	0.8	1.3	$3.9 \cdot 10^{-6}$	(31.8, 263.9)	19/20	(−7.8, 348.3)	$3.0 \cdot 10^{-5}$

Table 4: Significant sub-samples from the scan on redshift performed on the whole sample of 354 quasars and the northern and southern samples of 194 and 160 sources, respectively. Best cap parameters are shown as in Table 3 as well as the lower and upper limits in redshift of sub-samples. Note that region WCo is detected for $p_{lin} \leq 1.5\%$. Bold characters stress the most significant independent regions (see the text for a discussion).

not seem to be continuous: the alignment is present for some redshifts and not for others. In particular, all regions present alignments at small z_{min} , the northern hemisphere has one further clear alignment starting at $z = 1.3$, whereas the southern hemisphere has a significant alignment starting at $z = 0.8$. We see that for each sample, the redshift slices that show significant alignment are grouped in several islands in the (z_{min}, z_{max}) plane. For each island we retain the most significant sub-sample. The parameters of these nine sub-samples and of the corresponding most significant caps are given in Table 4. In this table, sub-samples are quoted by letter which indicates their original samples; namely, W, N and S indicate if they are extracted from the whole sky, from the northern sky or from the southern sky. Note that the sub-sample named WCo will be introduced and discussed in Section 3.3.

It maybe worth insisting on the fact that cuts in redshift, (or in declination and right ascension, see further subsections) amount to the consideration of data sub-samples with lower statistics. In that case, our method leads to higher values of p_{min} if an alignment effect is present, or to a similar value of p_{min} if there is no effect. The fact that one can markedly increase the significance of the effect by using such cuts indicates that the effect of alignment is stronger for some regions of redshift (or for some regions on the celestial sphere).

The first thing to notice is that we indeed find possible regions of alignment to the galactic South. However, we must decide whether they are all significant and independent, as a very significant region can always be somewhat extended by adding to it some noise. To decide, we can proceed as in the case of Fig. 6, and cut this time each sample in slices of redshift, declination and right ascension. The results of such a study are shown in Fig. 9 for all the regions of Table 4.

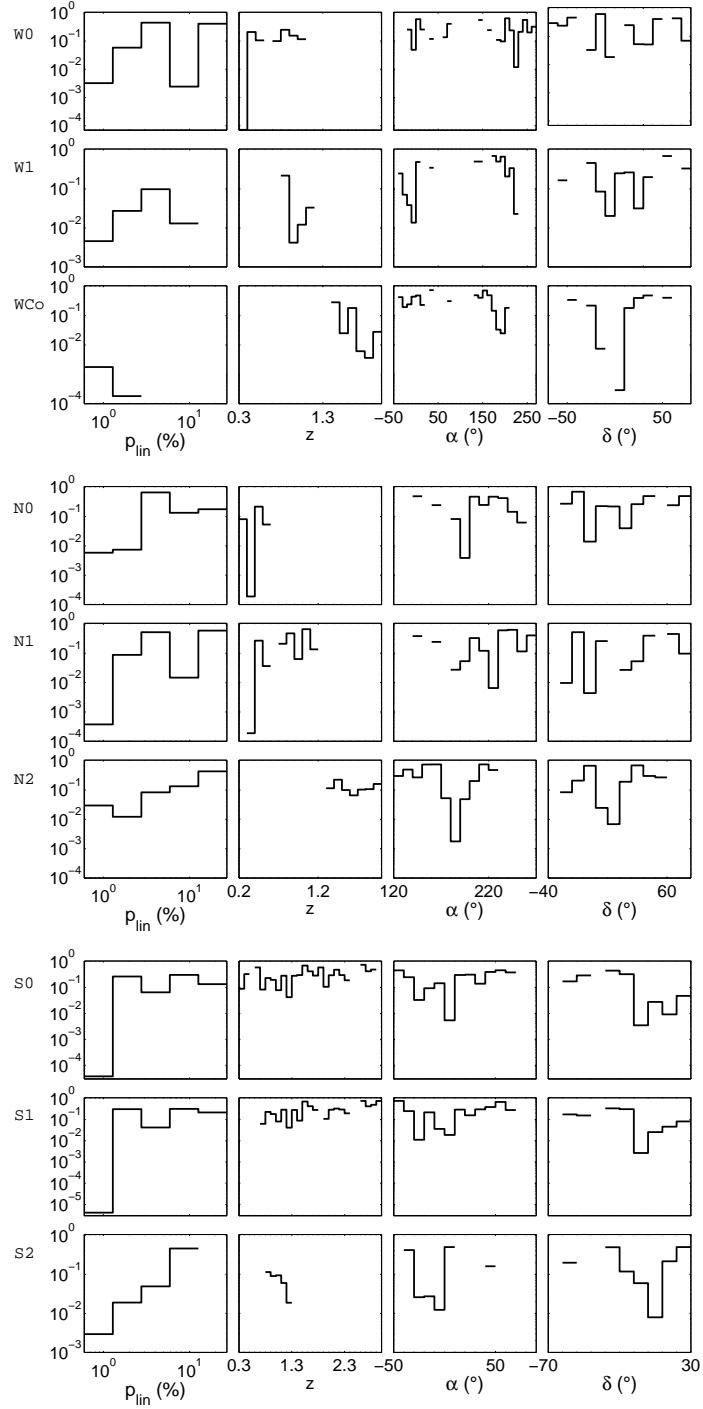


Figure 9: Fine structure of the regions of Table 4. The ordinates gives the p-values for excess in the sub-regions defined by the bins in the abscissae. Deficits are not shown.

If for now we concentrate on the last three columns of the southern regions (last three lines) in Fig. 9, we see the structure of S0, S1 and S2. The distributions in right ascension and declination tell us that the quasars that contribute most are in the same region of the

celestial sphere, which is confirmed by the 7th column of Table 4 that gives the average position on the sky. Also, the 5th column of Table 4 shows that the alignment is in the same direction for S0 and S1, and almost in the same direction for S2 (remember that the caps have an aperture of 45°). Hence it seems that there is a very strong alignment (to which 19 quasars out of 20 contribute) for the limited redshift region $0.8 < z < 1.3$, and that alignment can be extended to higher or lower redshift, without changing its significance much. As increasing the statistics should markedly decrease the p-value, we believe that only S2 is significant.

We can perform the same analysis for the northern quasars. Considering again the last three columns, and this time the fourth, fifth and sixth lines of Fig. 9, we see that N0 and N1 are populated by quasars in the same region of the celestial sphere, and that N1 is the same as N0, but extended in redshift. Table 4 confirms that the average position on the sky is very close, and that the preferred directions of polarisation are almost identical. It thus seems that N0 is the significant region, as N1 has more statistics, but less significance. On the other hand, Table 4 clearly shows that N2 is disjoint from N0 and N1 in redshift and that the preferred directions of alignments are significantly different. Indeed, the angular change is of the order of 70° which is reminiscent of result already obtained in [Hutsemékers et al. 2005].

Finally, we can consider the first two lines of Fig. 9. We see, looking at the plot in right ascension, that the most significant part of W0 is towards the galactic North, whereas W1 is more significant towards the galactic South. Table 4 shows that the direction of alignment of W0 (resp. W1) is compatible with that of N0 (resp. S2). Furthermore, we see that the most significant quasars of W0 fall in the same redshift bin as those of N0. Hence it seems that W0 is really a reflection of N0. Similarly, the p-values are smallest in W1 for the same redshifts as for S2, and it seems W1 is really generated by S2.

We have checked these conclusions by separating W0 and W1 into their northern and southern parts and by performing the study independently for these two parts. If p-values of both parts are all higher than the value of p_{min} of the whole, and point toward the same preferred direction, then it is clear that the observed alignment is produced by sources from both hemispheres. In the case of W0 (resp. W1) we find that the northern (resp. southern) alignment is much more significant.

3.2.1 Fine structure and best regions

We can study the structure of each region, and check whether it can be better defined by using further cuts. Consider the first column of Fig. 9, i.e. cuts on linear polarisation. We do not find, for N0, N2 and S2, that cuts in linear polarisation increase the effect significantly (i.e. that p_{min} gets reduced by more than a factor 2). The reduced significance of the bins with large polarisation is due to their lower statistics.

On the other hand, the dependence on right ascension and declination suggests that some regions of the sky are more significantly aligned. From this observation, we can define even more significant regions, by placing cuts on right ascension and declination. This does not lead to a significant difference, except for regions N2 and S2. Following the above argument, it seems we have detected three independent regions of alignment, which are significant. We summarise their parameters in Table 5. Note that N0, N2+ and S2+ are improved versions of A2, A1+ and A3 defined in [Hutsemékers et al. 2005].

Sample	z_{min}	z_{max}	p_{min}	$(\delta, \alpha)_{amin} (^\circ)$	o_a/o_a^{max}	δ interval ($^\circ$)	α interval ($^\circ$)	p^σ
N0	0.2	0.6	$1.4 \cdot 10^{-5}$	(15.0, 308.2)	28/37	$[-25, 80]^*$	$[135, 265]^*$	$1.8 \cdot 10^{-4}$
N2+	1.3	2.0	$4.5 \cdot 10^{-6}$	(79.8, 289.3)	30/35	$[-30, 35]$	$[165, 230]$	$5.0 \cdot 10^{-5}$
S2+	0.8	1.3	$1.9 \cdot 10^{-6}$	(31.8, 261.2)	18/18	$[-55, 25]^*$	$[-40, 20]$	$1.0 \cdot 10^{-5}$

Table 5: Best independent regions of alignment. The regions in δ, α marked by an asterisk describe the data sample, the others are cuts imposed on the data. N0 is the same as in Table 4. S2+ and N2+ are restrictions of S2 and N2 to a smaller region of the celestial sphere.

3.3 A possible cosmological alignment

Although cutting on polarisation does not improve significantly the previous probabilities, we detected a rather surprising alignment, as it is very significant only when the North sample is considered together with the southern one. Indeed, if we consider only small linear polarisations, with $p_{lin} \leq 1.5\%$, then there is a North-South alignment with a $p_{min} < 5 \cdot 10^{-6}$, as shown in the sample WCo of Table 4. This alignment is much less significant in the North ($p_{min} \approx 2 \cdot 10^{-4}$) or in the South ($p_{min} \approx 10^{-3}$), but it becomes significant once both hemispheres are considered together. It must also be noted that it is significant only after the cut on linear polarisation.

3.4 A naive interpretation

One can imagine that a systematic oscillating electric field \mathbf{E} is at work in each of the regions we defined. We can try to determine its norm and take it parallel to the centre of the polarisation cap $\hat{\mathbf{s}}_{centre}$, in such a way that the alignments we found disappear if we subtract that systematic effect from the samples we defined (in practice we impose that $p_{min} \geq 0.1$). Of course, we have first to project \mathbf{E} onto the plane normal to the direction of propagation, then remove it from the polarisation. If we perform this exercise, the resulting values of $|\mathbf{E}|$ are given in Table 6 for the most significant regions of Table 4. It is remarkable that the vectors we have to remove from the data have roughly the same norm. Due to the projection of the vector \mathbf{E} , this naive model could explain why polarisation vectors are not all seen to be aligned.

Sample	$ \mathbf{E} $ (%)
N0	0.65 – 0.70
N2	0.6 – 0.7
S2	0.8 – 1.2
WCo	0.5 – 0.9

Table 6: Norm of a systematic 3-vector accounting for the effect.

4 Conclusion

We have presented in this paper a new coordinate-invariant method to detect polarisation alignments in sparse data, and applied it to the case of alignments of optical polarisation vectors from quasars. We showed that we automatically recover regions previously found, and we refined their limits based on objective criteria (see Table 5). As a byproduct, the directions of alignments in space are unambiguously determined. The method we propose is powerful, as the coordinate-invariant significance levels are semi-analytically determined. The remaining drawback is that the determination of the global significance levels relies on very time-consuming Monte-Carlo simulations. We believe that this new analysis puts the alignment effect on stronger grounds as the global significance level is as low as $3.0 \cdot 10^{-5}$ for some regions of redshift.

However, one has to note that the significance levels obtained in this papers and those reported in [Hutsemékers et al. 2005] are not in full agreement. Indeed, the Z-type tests used in [Hutsemékers 1998] and [Jain, Narain & Sarala, 2004] reshuffle the measured polarisation directions while keeping the source locations to evaluate the background. The advantage is that any systematic effect vanishes automatically through this method. The disadvantage is that it washes out global effects, or alignments present for a large number of quasars. Random generation of polarisation angles, as used here or in [Jain, Narain & Sarala, 2004], has the opposite features: we can detect global alignments, but we are sensitive to systematic effects. Hence the two methods do not need to be in full agreement. One should note, however, that the sample of optical polarisation measurements of quasars considered here comes from many independent observational campaigns, so that a common bias is unlikely (see [Hutsemékers 1998] and [Hutsemékers et al. 2005] for discussion). Furthermore, [Jain, Narain & Sarala, 2004] have addressed this question of global systematic effect with the sample of 213 quasar polarisation measurements available at the time by comparing analyses of Z-type tests using uniform polarisation angle distribution and distribution made by reshuffling. They found that the significance level could decrease by factors of the order three. We expect this to be the case in this study. Note that this uncertainty is of the same order as that we estimated using the Jackknife algorithm.

Applying our method to the sample of 355 quasars compiled in [Hutsemékers et al. 2005], we identified the following main features. The directions of alignments show a dependence on the redshift of the sources. Although this dependence seems discontinuous, one should note that we detected significant alignments for redshift intervals where the distribution of data peaks. Thus, more data in regions of redshift with poor statistics are required in order to study this dependence in more details. As seen in Fig. 9, for a given redshift interval, alignment seems to be mainly due to quasars well localized toward specific directions of the sky. Furthermore, no strong evidence has been found for a dependence on the degree of linear polarisation.

As a result of the application of our new method to the present sample of optical polarisation measurements of quasars, and in agreement with [Hutsemékers et al. 2005], we found several distinct sub-samples of sources well localized in redshift and position on the sky that show unexpected alignments of their polarisation vectors. We established two regions towards the North galactic pole, one at low and the other at high redshift, and only

one towards the South galactic pole at intermediate redshift, which possibly dominates the whole southern sky. Besides the regions previously detected, or their improved version, we also showed that there exists the possibility of a cosmological alignment.

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